The Nucleus as a Laboratory for Measuring the Fundamental Properties of the Neutrino

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RNC-Future Discussion Forum
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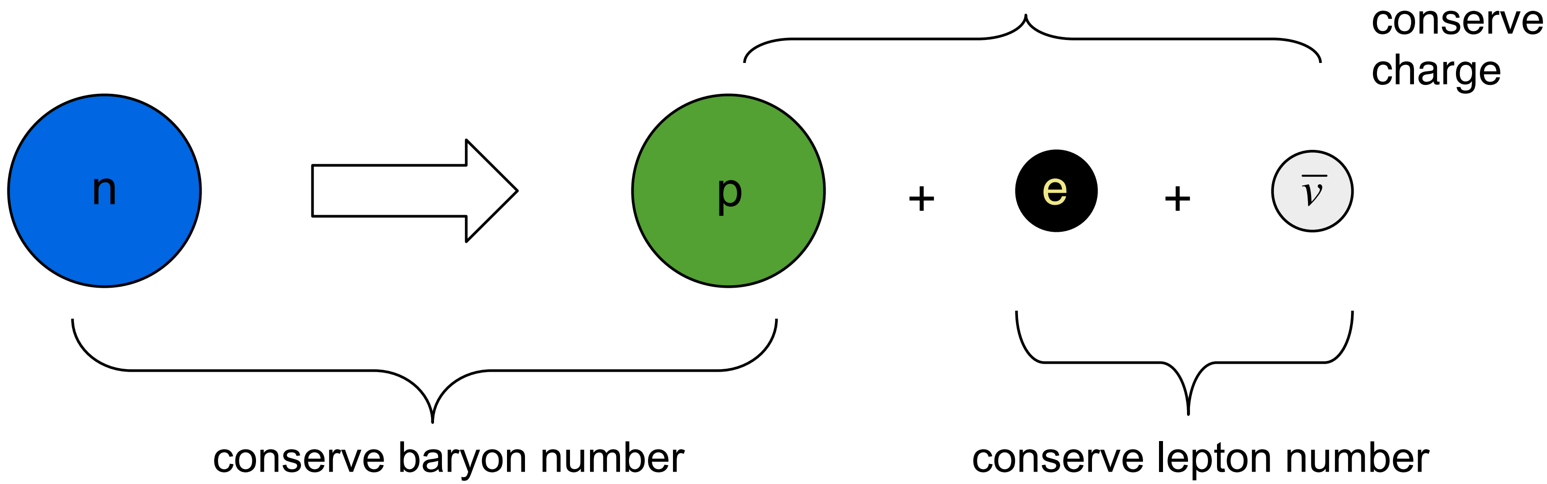
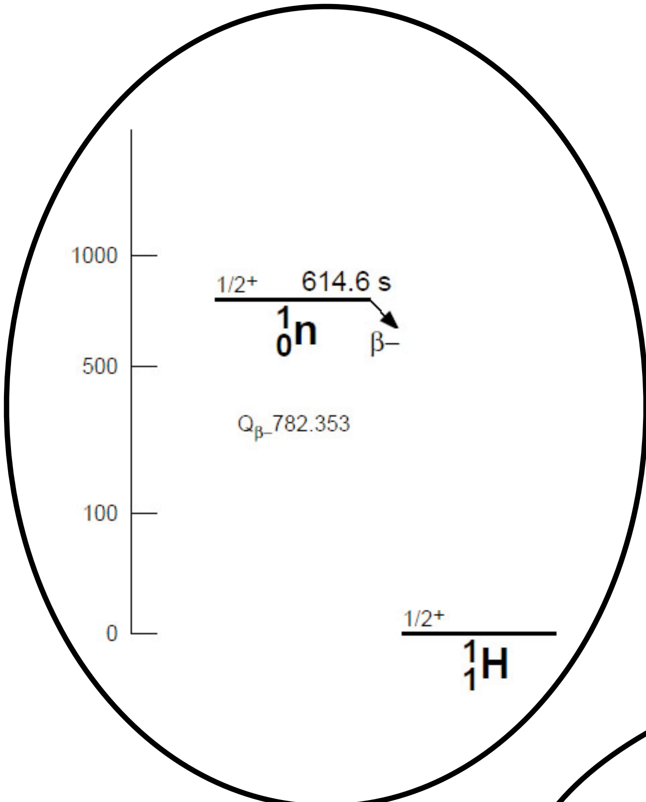
The Neutron

- **A free neutron is not stable and will decay**
  - **The half life is 614.6 seconds**
    - **A very human scale … about equal to the attention span of a full professor of physics**
  - **$c\tau$ = 2.65 x 10^8 km**



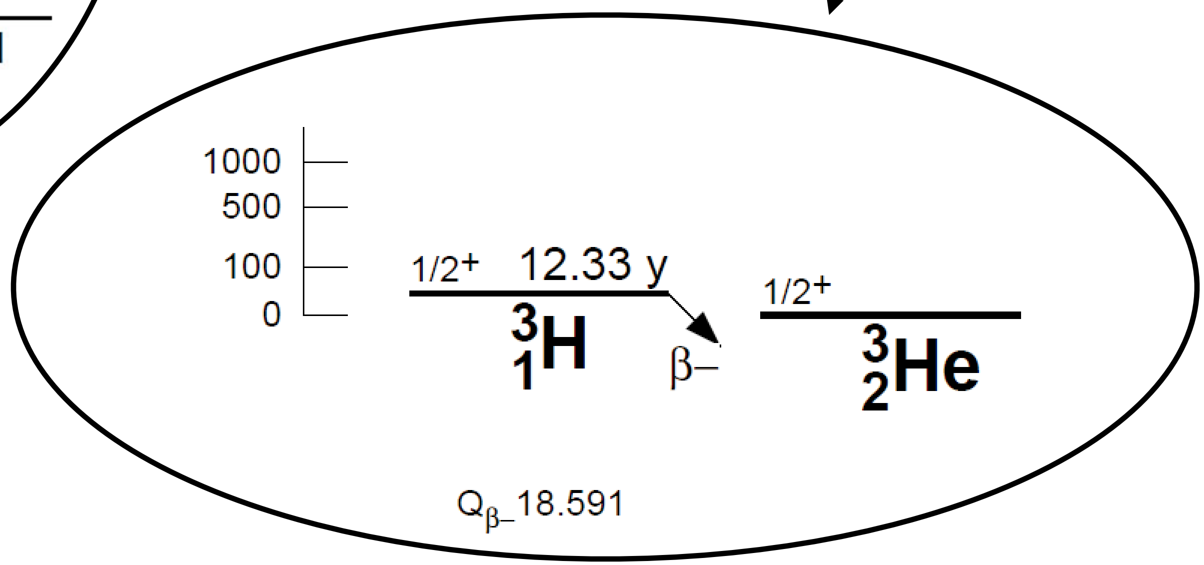
- **Also conserve energy: a free neutron is <u>heavier</u> than a free proton**
  - **The neutron is heavier by 1.29 MeV. This is surprising because the proton includes the self energy of the Coulomb interaction**
  - **Note that charged pions are heavier than neutral pions by 4.59 MeV**
  - **Which tells you that the neutron has substructure …**

The neutron inside a nucleus is (almost) stable



The energy level diagram for the decay of a free neutron

Tritium is one proton outside a spherical core of neutrons … the neutrons are stabilized by the strong force



Tritium Beta Decay can be used to measure m_ν

- **Use Fermi's Golden Rule to calculate the transition rate**

$$\lambda = \frac{4\pi^2}{h}\left|M_{fi}\right|^2 \frac{dN}{dE_f}$$

- **Honor kinematics of the decay**

$$\left.\begin{aligned} E_f &= E_R + E_\nu + E_e \\ 0 &= \vec{P} + \vec{p} + \vec{q} \end{aligned}\right\} \text{ Conservation laws}$$

$$M_R \rangle\rangle m_e \Rightarrow E_f \rangle\rangle E_R \approx 0 \quad \} \text{ Approximations}$$

Now calculate desity of states

$$\rho = \frac{dN}{dE_f}$$

$$dN_e = 4\pi p^2 dpV / h^3$$

$$dN_\nu = 4\pi q^2 dqV / h^3$$

$$d^2N = 4\pi p^2 dpV / h^3 * 4\pi q^2 dqV / h^3$$

Convert to $dpdE_f$

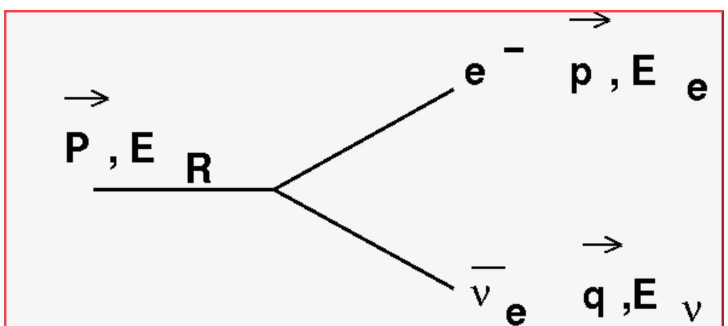
Crank and Grind to find:

$$\boxed{\lambda = G_F^2 \frac{m_e^5 c^4}{2\pi^3 \hbar^7} \cos^2(\theta_c) F(Z,E_e)\left|M_{fi}\right|^2 \underbrace{pE_e(E_0 - E_e)\left[(E_0 - E_e)^2 - m_\nu^2\right]^{1/2}}}$$

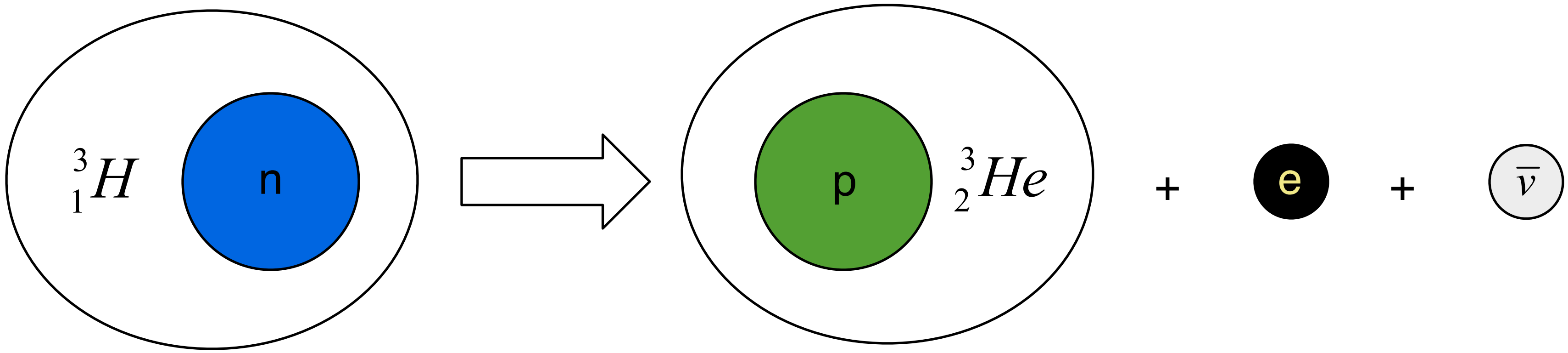
Mass sensitive terms … $E_0 \equiv$ endpoint energy = E_f

Nuclear matrix elements representing the re-arrangement of the nucleons before and after the decay

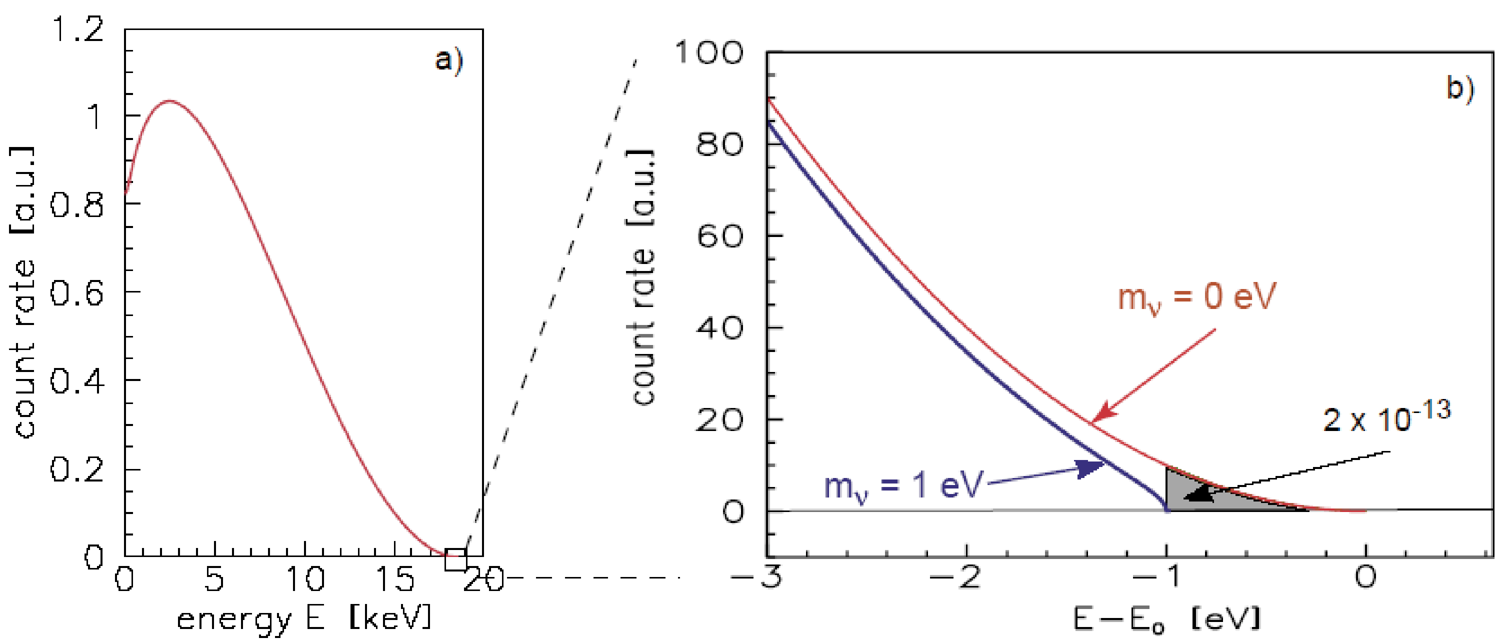
Fermi function representing the Coulomb interaction between the electron and the nucleus



Tritium Beta Decay – direct mass limit < 2.2 eV



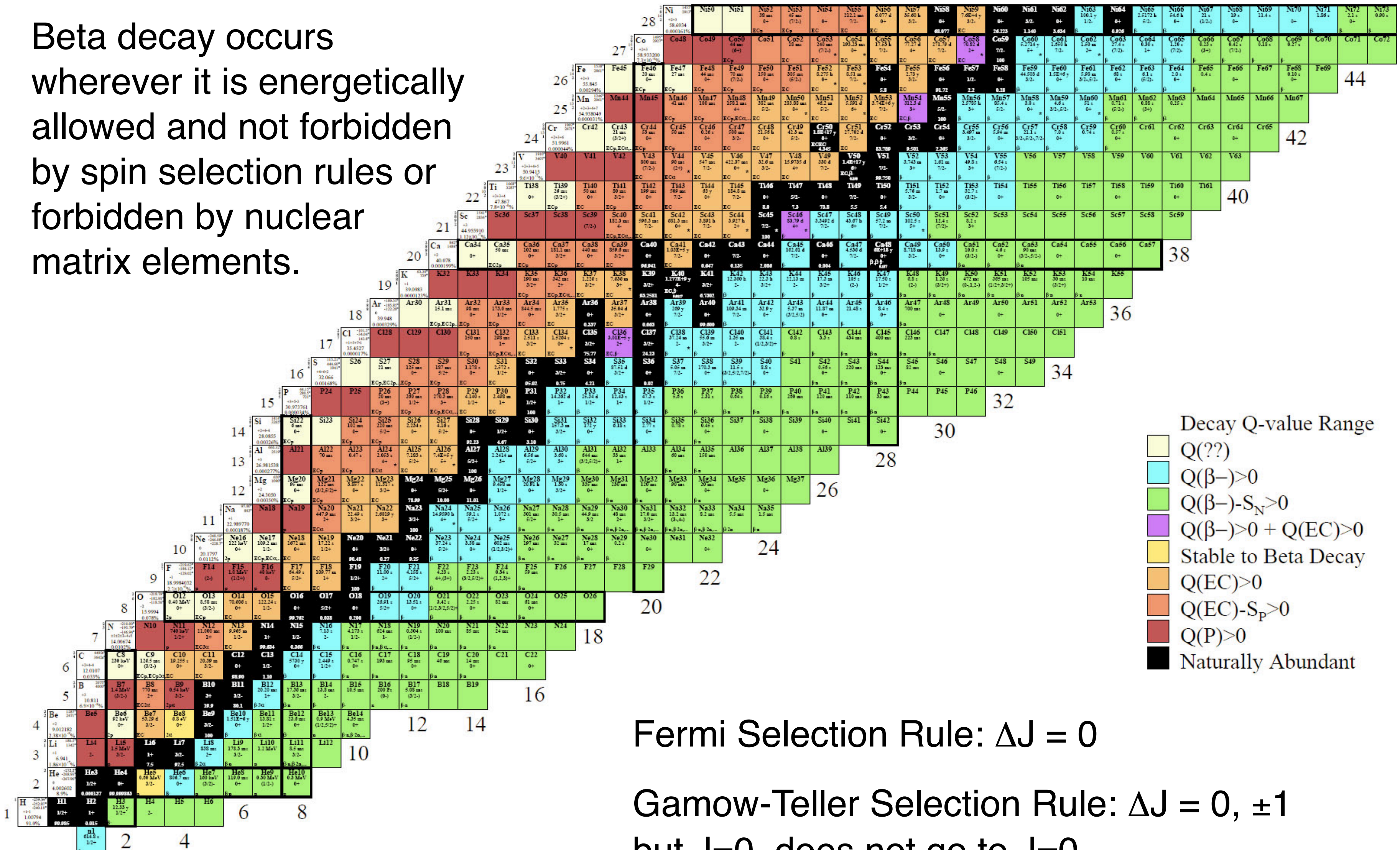
$$\lambda : (E_0 - E_e)\left[(E_0 - E_e)^2 - m_\nu^2\right]^{1/2}$$



Jim Thor

Table of the Isotopes

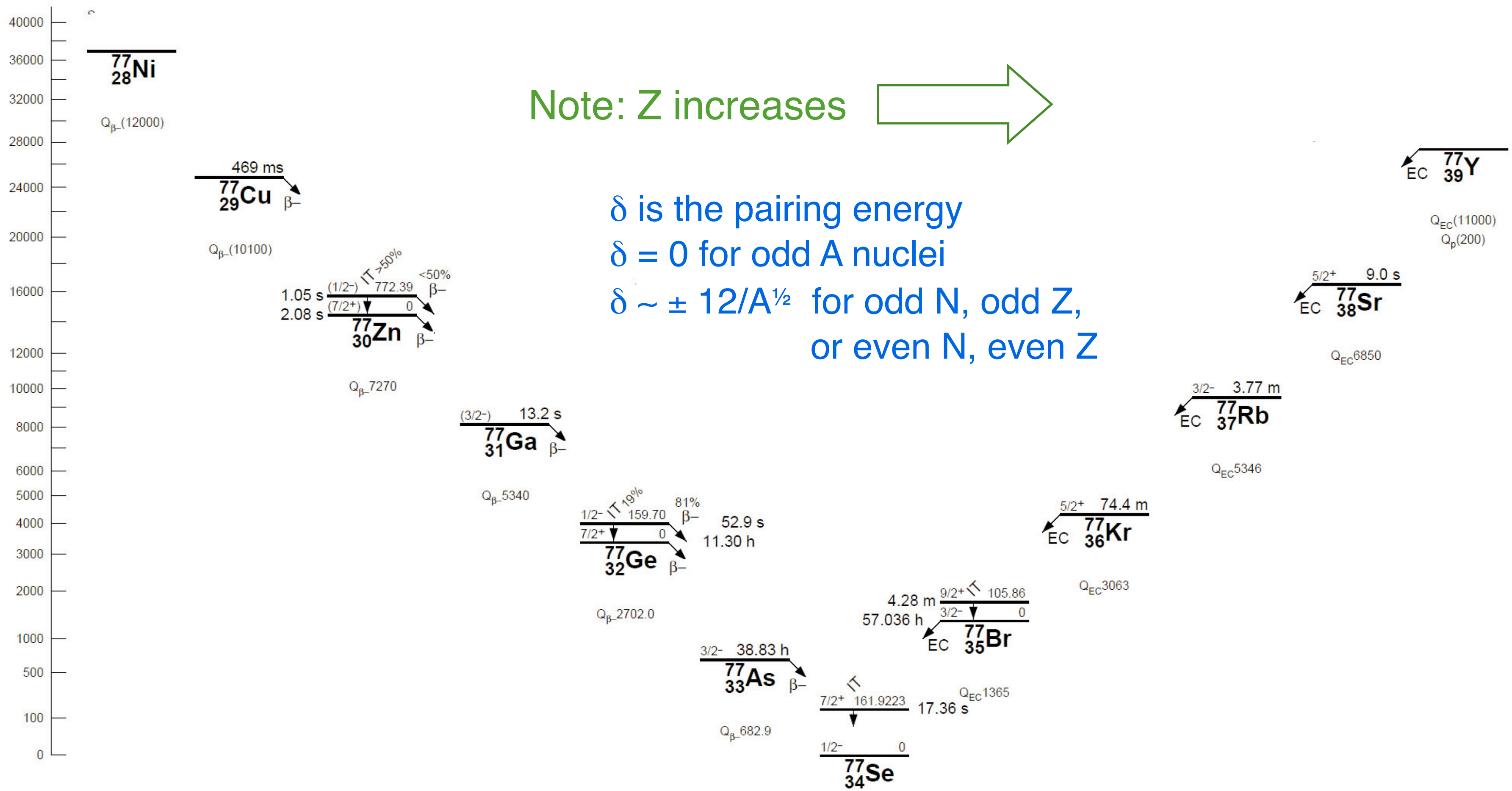
Beta decay occurs wherever it is energetically allowed and not forbidden by spin selection rules or forbidden by nuclear matrix elements.



Fermi Selection Rule: $\Delta J = 0$

Gamow-Teller Selection Rule: $\Delta J = 0, \pm 1$
but J=0 does not go to J=0

The Valley of Stability at A = 77



Note: Z increases

δ is the pairing energy

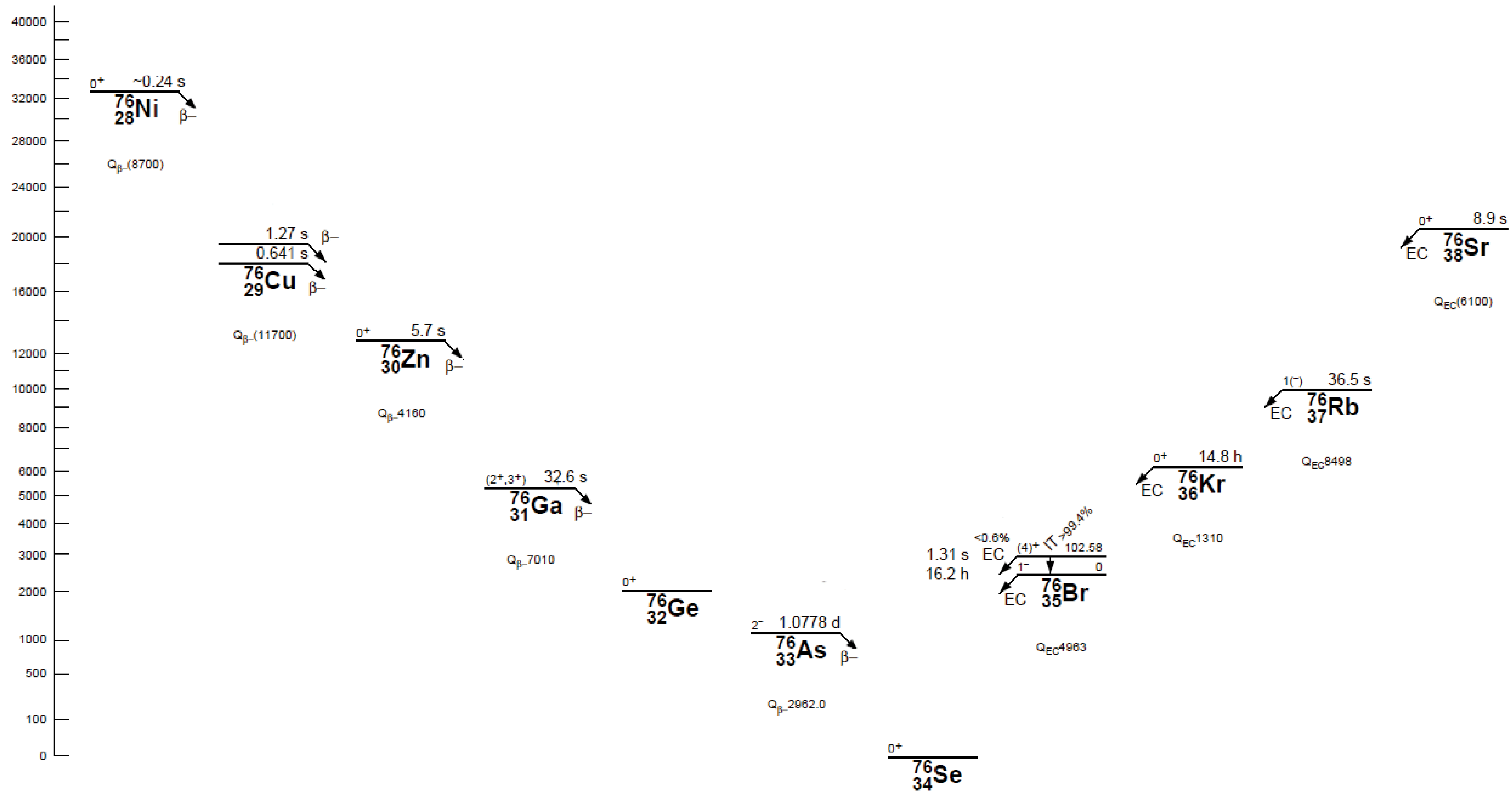
δ = 0 for odd A nuclei

δ ~ ± 12/A½ for odd N, odd Z, or even N, even Z

$$M_A = const. + 2b_{symmetry}\frac{(A/2 - Z)^2}{A^2} + b_{Coulomb}\frac{Z^2}{A^{1/3}} + m_e Z + \delta$$

$$b_{symmetry} \approx 50\ MeV \quad and \quad b_{Coulomb} \approx 0.7\ MeV$$

The Pairing of Nucleons is Important (A = 76)



The pairing energy, δ, can create a situation where β decay is kinematically forbidden.

Double Beta Decay is Energetically Allowed

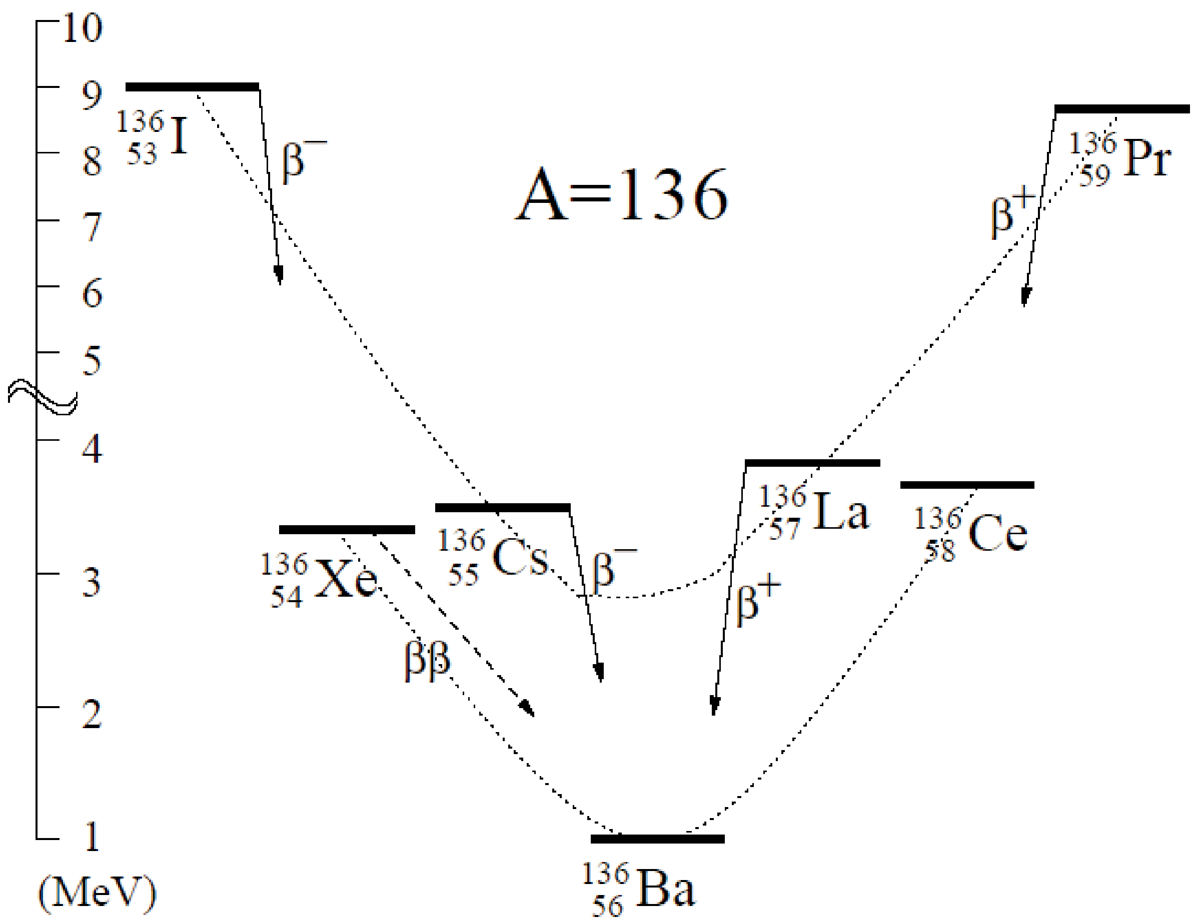
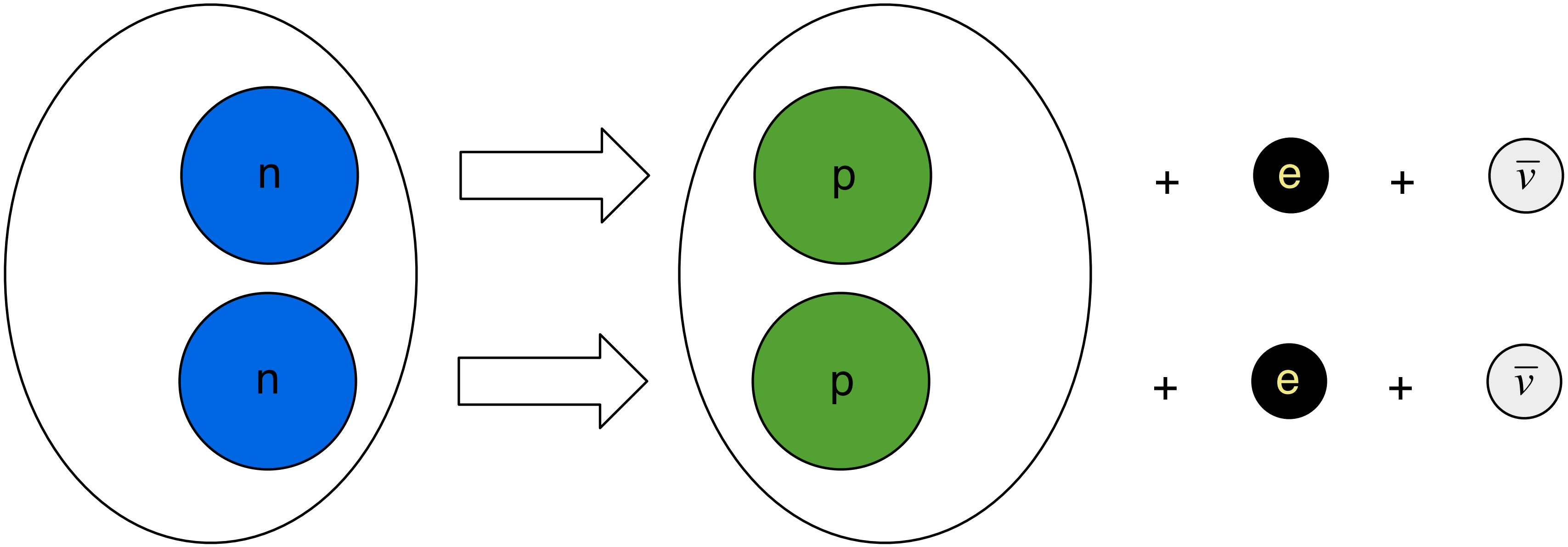


Figure 2: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable for ordinary β^- decay, it can decay into ^{136}Ba by a double-beta process.

Two Neutrino Double Beta Decay is Allowed



- **Two neutrino double beta decay is a 2nd order weak decay**
  - **It is an allowed decay (in terms of spin selection rules)**
  - **It proceeds via virtual states in the intermediate nucleus**

$$d\lambda = 2\pi \; \delta\left(E_0 - \sum_f E_f\right) \left| \sum_{m,\beta} \frac{< f \,|\, H_\beta \,|\, m >< m \,|\, H^\beta \,|\, i >}{E_i - E_m - p_\nu - E_e} \right|^2$$

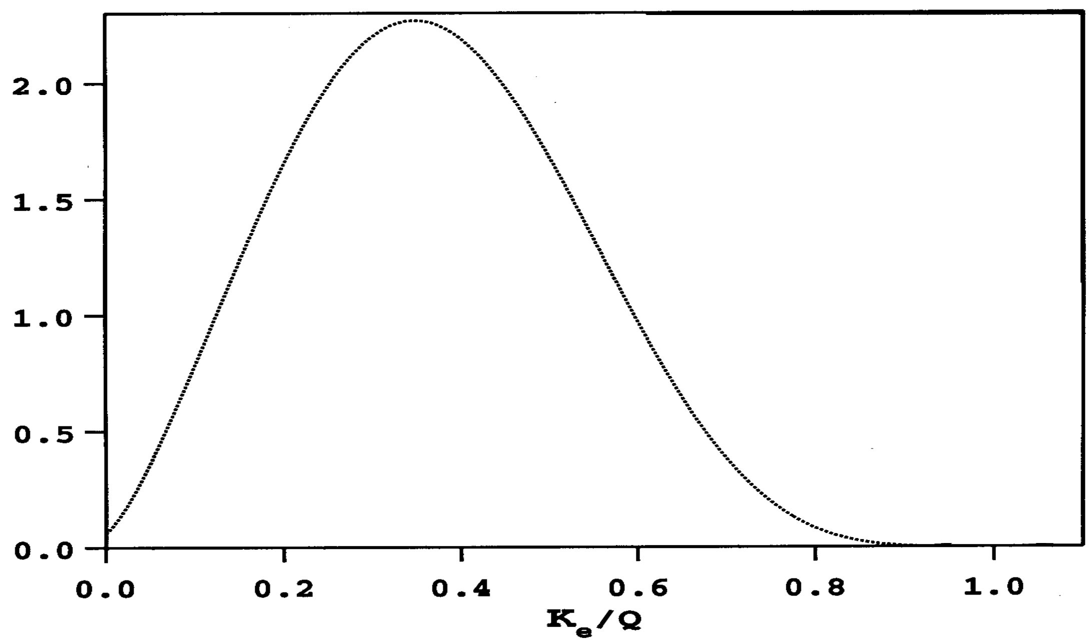
- **It produces <u>two electrons and two neutrinos in the final state</u>**
  - **First discussed by M. Goeppert-Mayer in 1935 and predicted to have a half life > 10^{20} years. It has been observed in ^{100}Mo**

^{100}Mo

Rh95 5.02 m (9/2)+ * EC	**Rh96** 9.90 m 6+ * EC	**Rh97** 30.7 m (9/2)+ * EC	**Rh98** 8.7 m (2)+ * EC	**Rh99** 16.1 d 1/2- * EC	**Rh100** 20.8 h 1- * EC	**Rh101** 3.3 y 1/2- * EC	**Rh102** 207 d (1-,2-) * EC,β^-	**Rh103** 1/2- * 100	**Rh104** 42.3 s 1+ * EC,β^-	**Rh105** 35.36 h 7/2+ * β^-	**Rh106** 29.80 s 1+ * β^-	**Rh107** 21.7 m 7/2+ β^-
Ru94 51.8 m 0+ EC	**Ru95** 1.643 h 5/2+ EC	**Ru96** 0+ 5.52	**Ru97** 2.9 d 5/2+	**Ru98** 0+ 1.88	**Ru99** 5/2+ 12.7	**Ru100** 0+ 12.6	**Ru101** 5/2+ 17.0	**Ru102** 0+ 31.6	**Ru103** 39.26 d 3/2+ * β^-	**Ru104** 0+ 18.7	**Ru105** 4.44 h 3/2+ β^-	**Ru106** 373.59 d 0+ β^-
Tc93 2.75 h 9/2+ * EC	**Tc94** 293 m 7+ * EC	**Tc95** 20.0 h 9/2+ * EC	**Tc96** 4.28 d 7+ * EC	**Tc97** 2.6E6 y 9/2+ * EC	**Tc98** 4.2E+6 y (6)+ β^-	**Tc99** 2.111E+5 y 9/2+ * β^-	**Tc100** 15.8 s 1+ β^-	**Tc101** 14.22 m (9/2)+ β^-	**Tc102** 5.28 s 1+ * β^-	**Tc103** 54.2 s 5/2+ β^-	**Tc104** 18.3 m (3+) β^-	**Tc105** 7.6 m (3/2-) β^-
Mo92 0+ 14.84	**Mo93** 4.0E+3 y 5/2+ * EC	**Mo94** 0+ 9.25	**Mo95** 5/2+ 15.92	**Mo96** 0+ 16.68	**Mo97** 5/2+ 9.55	**Mo98** 0+ 24.13	**Mo99** 65.94 h 1/2+ β^-	**Mo100** 1.2E19 y 0+ $\beta^-\beta^-$ 9.63	**Mo101** 14.61 m 1/2+ β^-	**Mo102** 11.3 m 0+ β^-	**Mo103** 67.5 s (3/2+) β^-	**Mo104** 60 s 0+ β^-
Nb91 680 y 9/2+ * EC	**Nb92** 3.47E+7 y (7)+ * EC,β^-	**Nb93** 9/2+ * 100	**Nb94** 2.03E+4 y (6)+ * β^-	**Nb95** 34.975 d 9/2+ * β^-	**Nb96** 23.35 h 6+ β^-	**Nb97** 72.1 m 9/2+ * β^-	**Nb98** 2.86 s 1+ * β^-	**Nb99** 15.0 s 9/2+ * β^-	**Nb100** 1.5 s 1+ * β^-	**Nb101** 7.1 s + β^-	**Nb102** 1.3 s 1+ * β^-	**Nb103** 1.5 s (5/2+) β^-
Zr90 0+ * 51.45	**Zr91** 5/2+ 11.22	**Zr92** 0+ 17.15	**Zr93** 1.53E+6 y 5/2+ β^-	**Zr94** 0+ 17.38	**Zr95** 64.02 d 5/2+ β^-	**Zr96** 3.9E19 y 0+ β^- 2.80	**Zr97** 16.91 h 1/2+ β^-	**Zr98** 30.7 s 0+ β^-	**Zr99** 2.1 s (1/2+) β^-	**Zr100** 7.1 s 0+ β^-	**Zr101** 2.1 s (3/2+) β^-	**Zr102** 2.9 s 0+ β^-
Y89 1/2- * 100	**Y90** 64.10 h 2- * β^-	**Y91** 58.51 d 1/2- *	**Y92** 3.54 h 2- β^-	**Y93** 10.18 h 1/2- * β^-	**Y94** 18.7 m 2- β^-	**Y95** 10.3 m 1/2- β^-	**Y96** 5.34 s 0- * β^-	**Y97** 3.75 s (1/2-) * β^-n	**Y98** 0.548 s (0)- * β^-n	**Y99** 1.470 s (5/2+) β^-n	**Y100** 735 ms 1-,2- * β^-n	**Y101** 448 ms (5/2+) β^-n

^{100}Mo is not stable. But it is naturally abundant because its half life is greater than the age of the Universe.

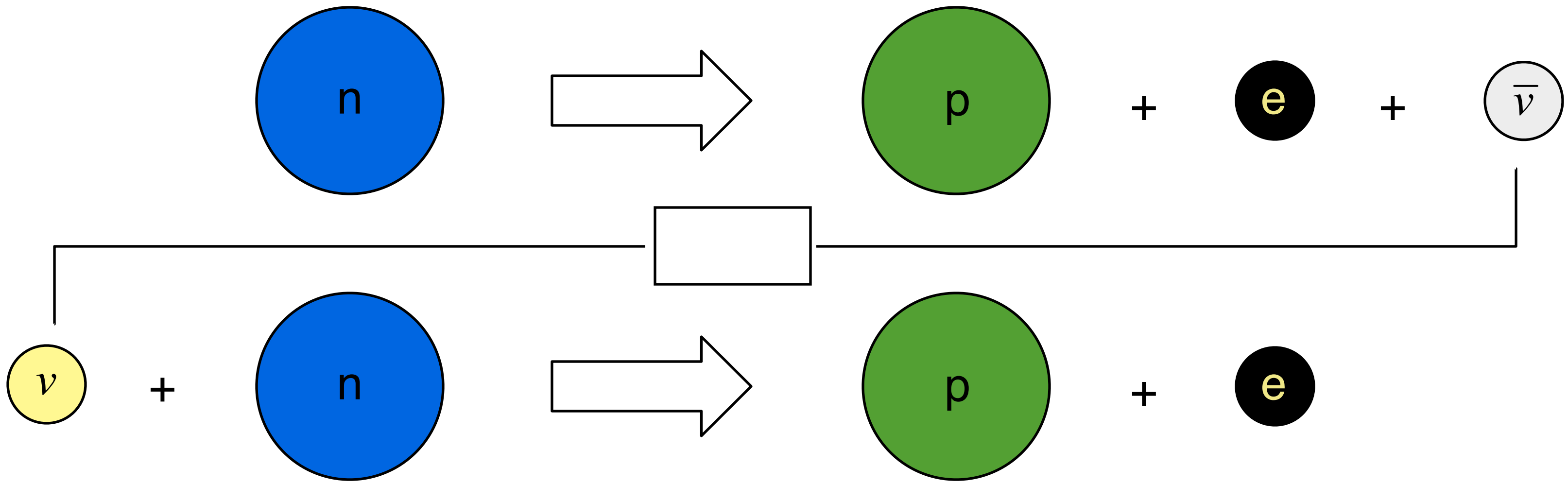
Two ν Double Beta Decay is a 4 Body Process



- The summed energy of the 2 electrons in the final state is a broad spectrum that reaches from 0 to T_0 where T_0 is the kinematically allowed endpoint (shown as 1.0 in the figure).

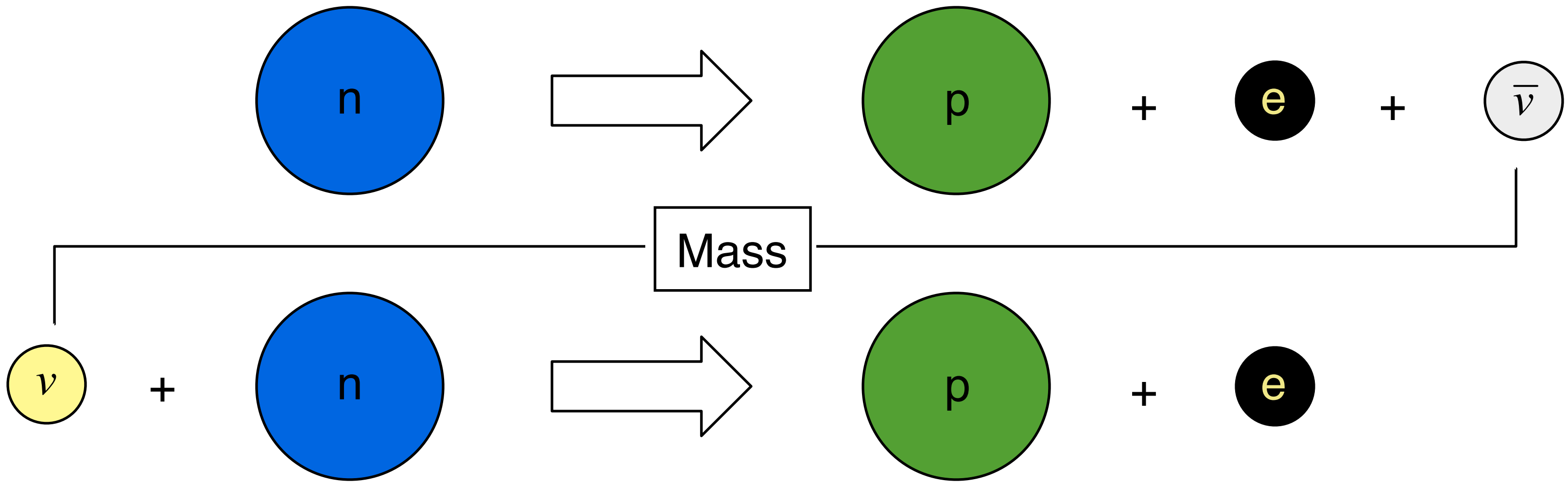
- The decay rate depends on T_0^{11} and so there is great advantage to studying nuclear systems where the decay energy is large (typically a few MeV).

Zero Neutrino Double Beta Decay



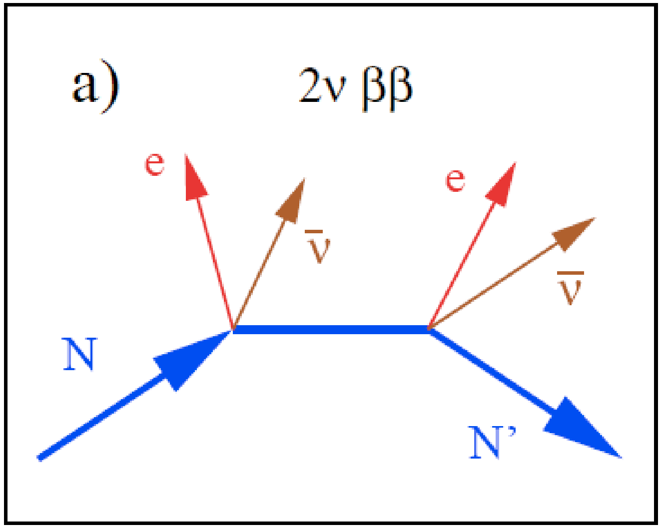
- **Zero neutrino double beta decay can occur if the anti-neutrino from one beta decay can be used to stimulate the decay of a second neutron in the same nucleus.**
  - **This process has two electrons in the final state and no neutrinos**
  - **It violates lepton number conservation**
- **To do this, the neutrino must be its own anti-particle (a Majorana particle)**
  - **There must be a solution to the helicity problem, too.**
  - **One solution to this problem is m_ν**

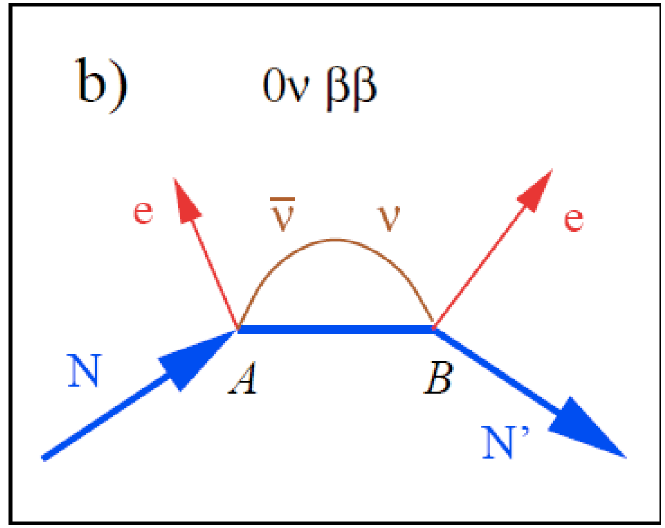
Zero Neutrino Double Beta Decay

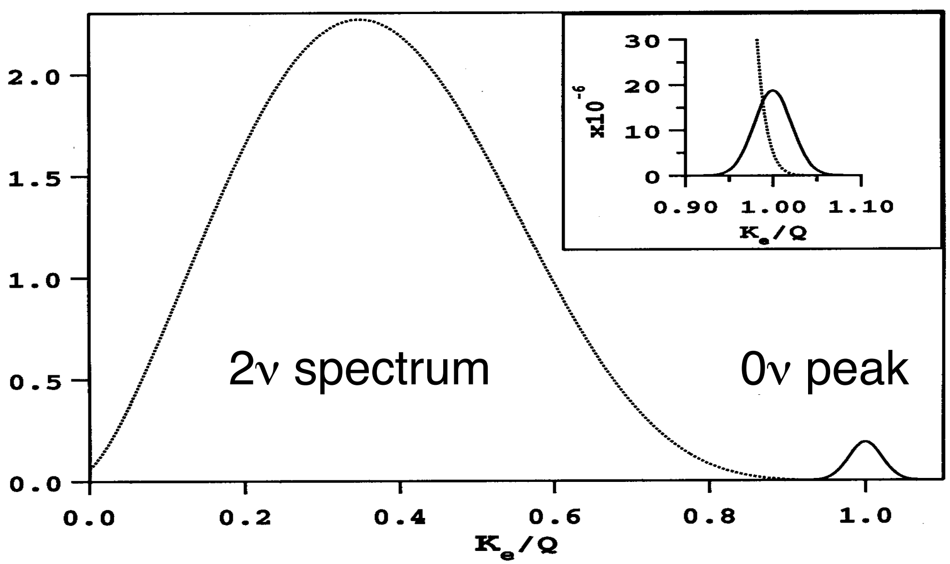


- The neutrino is left handed (spin opposite the direction of motion). The anti-neutrino is right handed (spin in the direction of motion).
  - They must be identical for 0ν double beta decay to occur
- If the ν is massive, then its velocity must be less than c and there exists a frame which is going faster than the ν. If the velocity of the frame exceeds the velocity of the ν then the ν appears to be going the other way in the new frame. In other words, its helicity is flipped.
- Mass + the Lorentz transformation is a mechanism to solve the helicity problem if the neutrino is a Majorana particle.

Two Modes of Double Beta Decay, 2ν and 0ν







- **The two modes can be distinguished by the summed energy of the electrons in the final state.**
- **The 0ν decay is identified as the narrow peak at the kinematic limit of the decay process.**

Candidate Nuclei for Double Beta Decay (Q > 2)

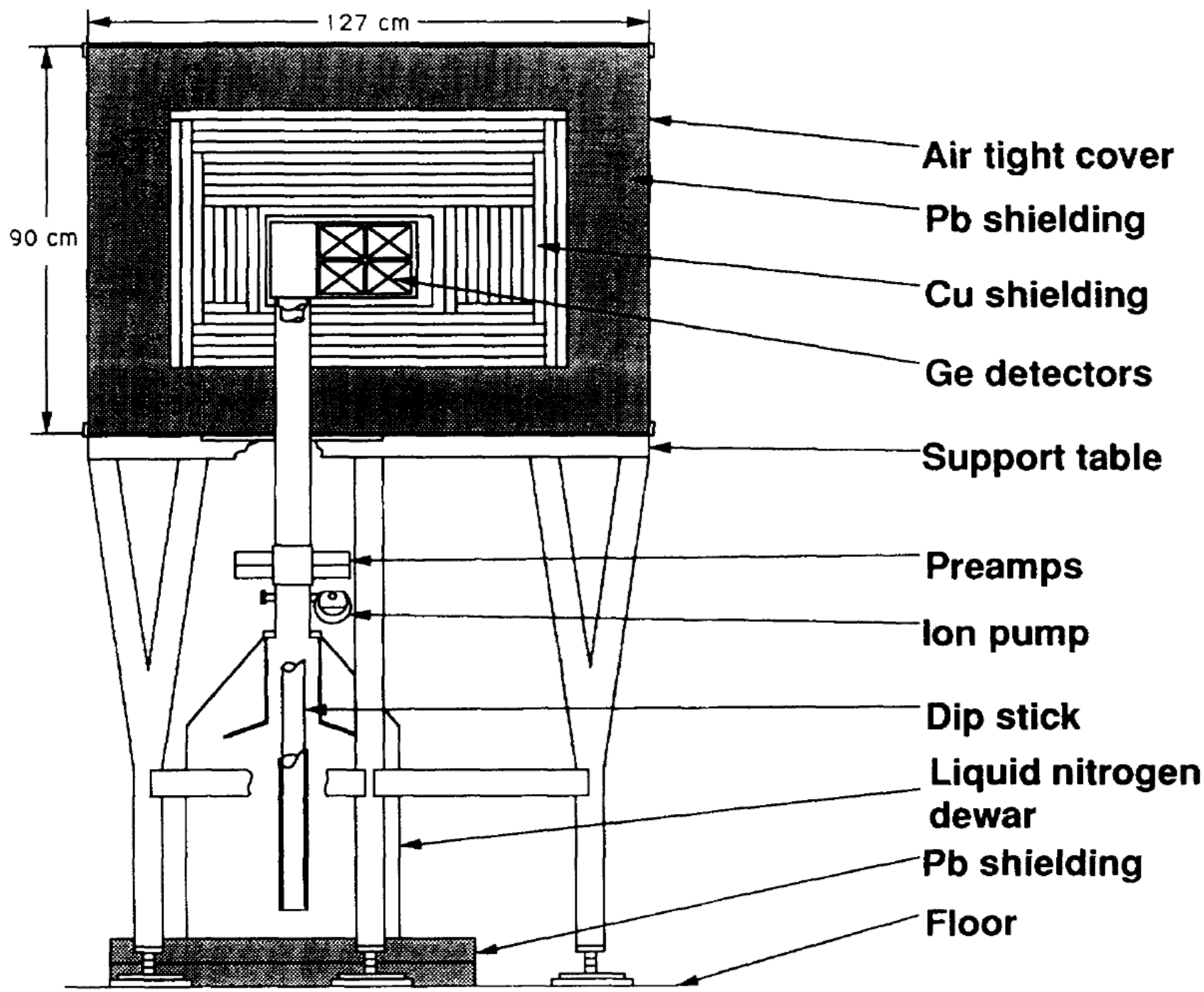
Candidate	Q (MeV)	Abundance (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Issues include :

Q value, abundance, ease of purification (chemical and isotopic), radioactivity (incl. cosmogenesis), & experimental ease of use.

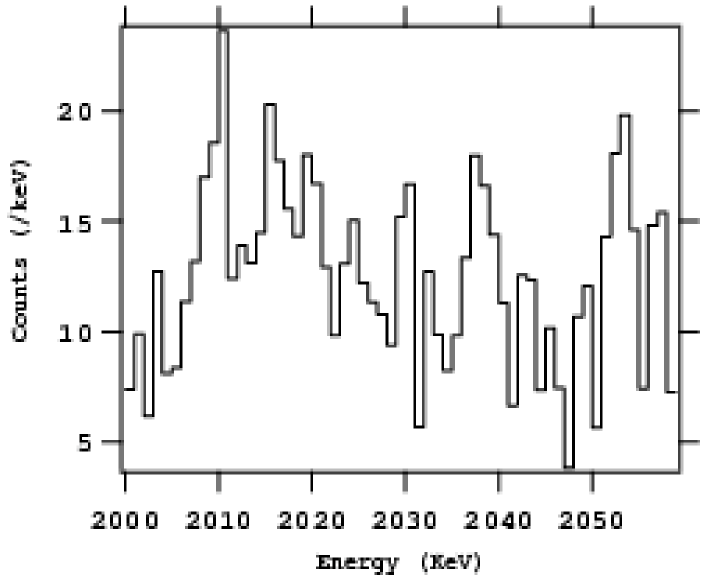
^{76}Ge is the Simplest 0ν ββ Experiment

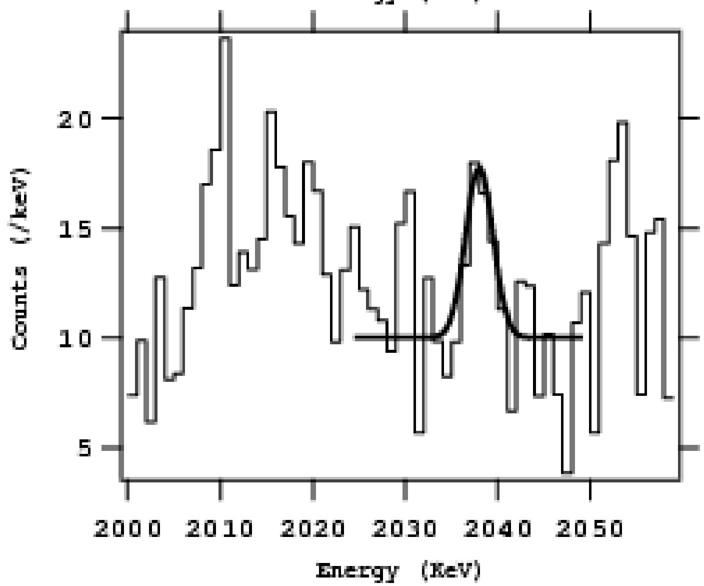
- **Germanium diode detectors are readily available**
  - The Ge is the source and the detector
  - High resolution
  - High Purity
  - Merely requires adequate shielding from Cosmic rays (etc.)
- **The experiment has been done several times**
  - mass limits less than 1 eV
  - possibly even a positive result



Neuchatel-Caltech-PSI Collaboration @ Gotthard Tunnel

Possibly a positive result in ^{76}Ge





From Klapdor-Kleingrothaus, Dietz, Krivosheina, Chkvorets, hep-hp/0403018.

71.7 kg-y exposure with enriched Ge

Spectrum shown with and without the proposed peak

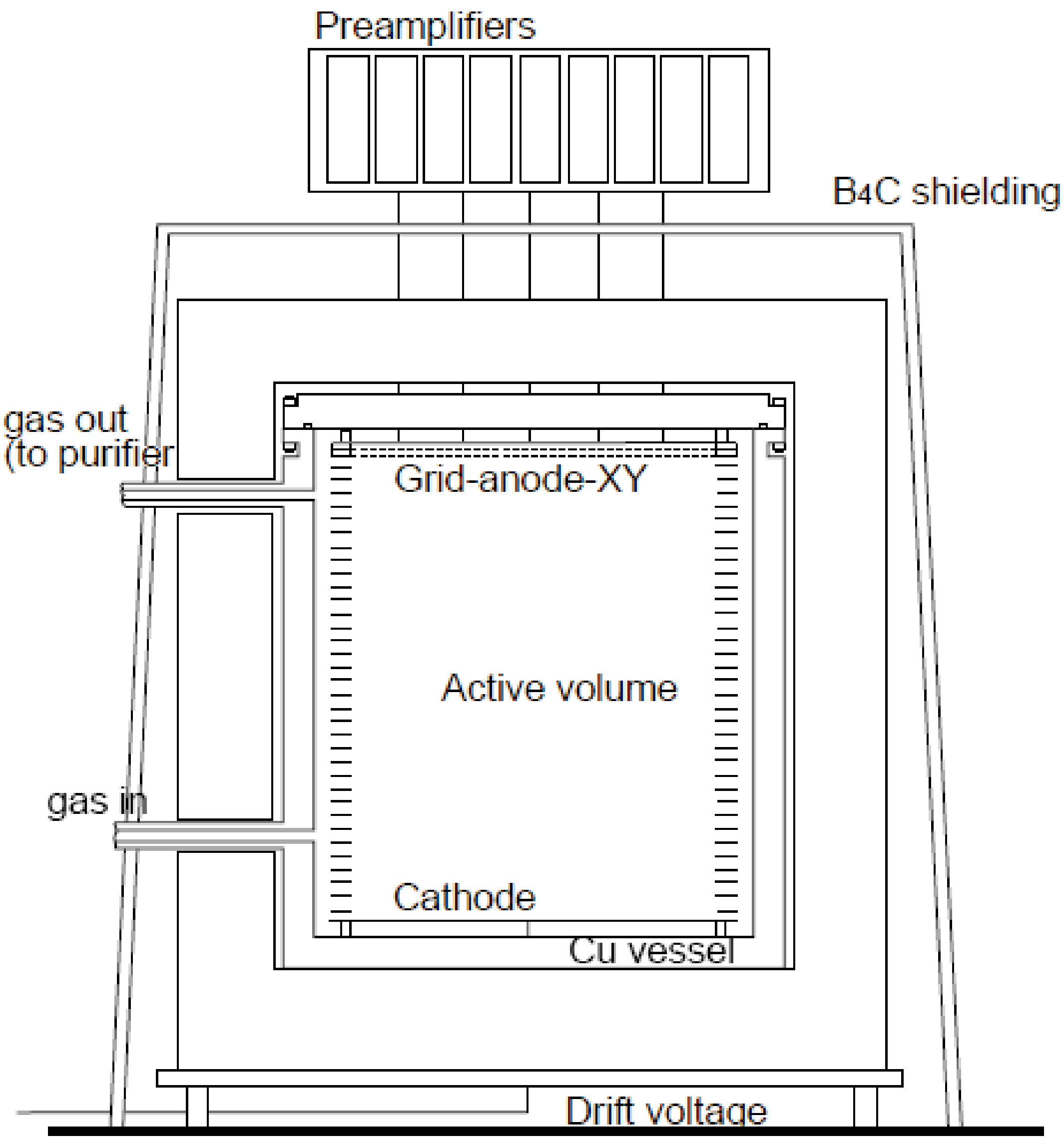
Additional lines at 2010, 2017, 2022, 2053 are assigned to the ^{214}Bi decay. The line at 2030, is of an unknown origin.

But it's a very tricky business …

Background is the key issue in a rare event search

And that's where all the work goes

^{136}Xe TPC – the source is the detector



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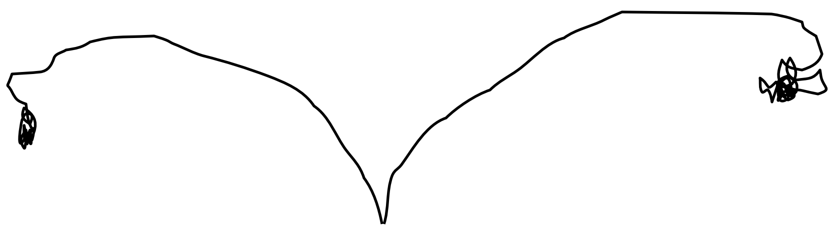
^{136}Xe: The signal

- The signal is two electrons from a common vertex
- Their summed energy should equal 2.479 MeV



- The electron identification can be enhanced by accepting candidate tracks that have a large amount of MCS and large dE/dx near the end point of each track
  - The electron passes over the Bragg Maximum in the dE/dx curve
- This is a high event rate experiment
  - About one candidate per week

^{136}Xe: A Candidate Event

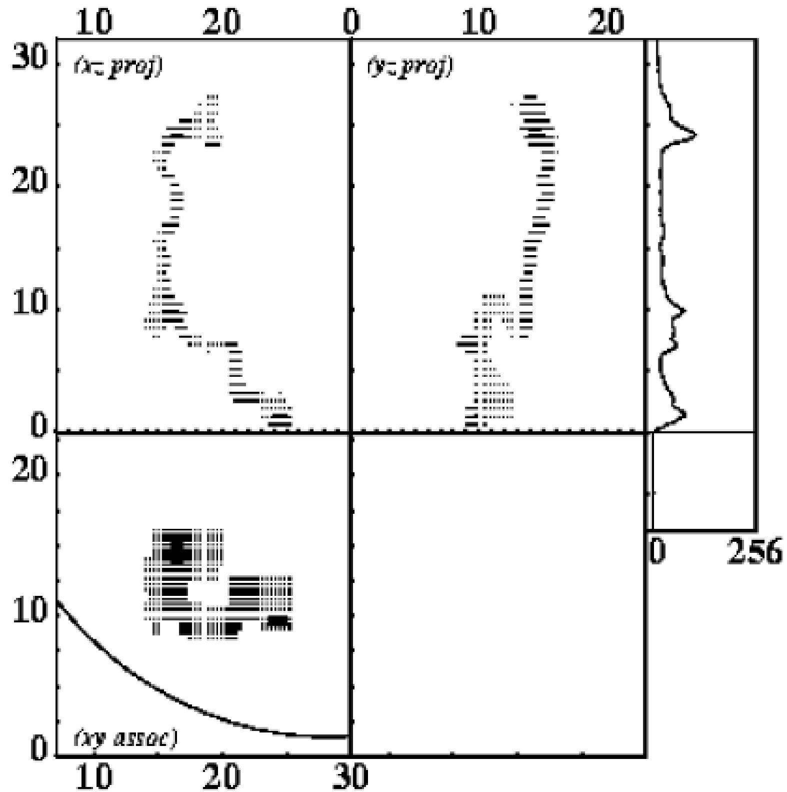


Figure 6: Electron tracks from a candidate double-beta decay event in xenon from [24]. The two main top panels show the xz and yz projections of the event, while the reconstructed xy view is given in the bottom part (dimensions are in cm). Pulse-height information is shown in the smaller panel on the right (in ADC counts). Note the higher ionization density at the end of the tracks. The circular sector in the bottom-left corner of the xy view represents the edge of the TPC.

Present Limits for 0ν double beta decay

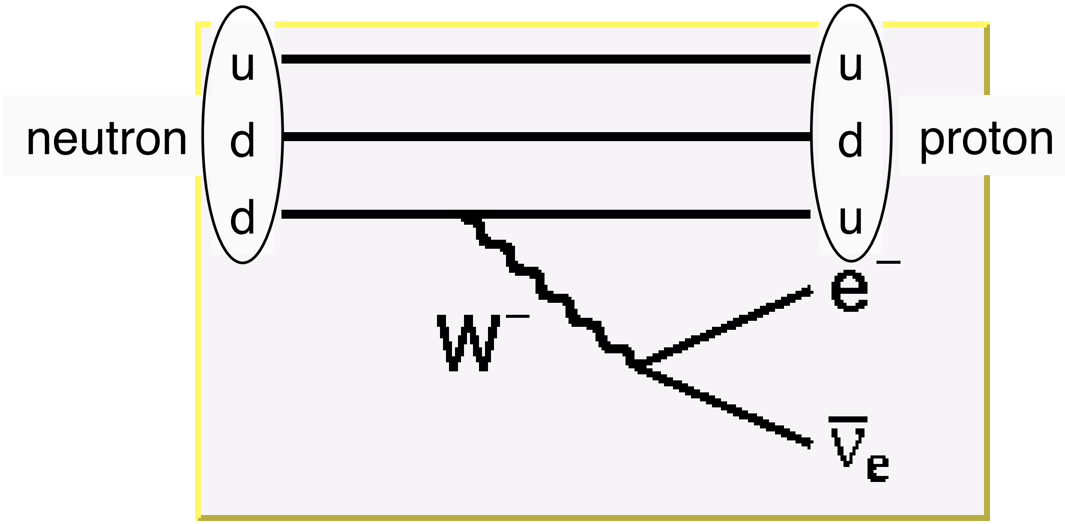
Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV) QRPA	NSM
^{48}Ca			$9.5*10^{21}$ (76%CL)		
^{76}Ge	Ge diode	~30	$1.9*10^{25}$ (90%CL)	0.35	1.0
^{82}Se			$2.7*10^{22}$ (68%CL)		
^{100}Mo			$5.2*10^{22}$ (68%CL)		
^{116}Cd			$7.0*10^{22}$ (90%CL)		
^{130}Te	TeO_2 cryo	~1	$1.4*10^{23}$ (90%CL)	1.1	2.6
^{136}Xe	Xe TPC	~8	$4.4*10^{23}$ (90%CL)	1.8	5.2
^{150}Nd			$1.2*10^{21}$ (90%CL)		

Conclusion

The observation of $0\nu\ \beta\beta$ would:

3. Establish the neutrino as a massive Majorana particle.
4. Demonstrate lepton number violation.
5. Determine the absolute mass scale for neutrinos.
6. Provide clues to the values of the Majorana phases in the mixing of neutrino eigen states that we are actually observed in nature

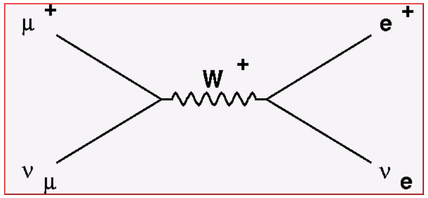
Elementary Particle Explanation of n Decay



- The conversion of a <u>down</u> quark into an <u>up</u> quark proceeds via the emission of a massive intermediate vector boson

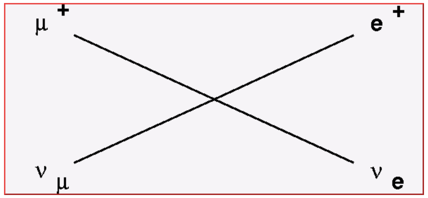
V-A Theory

- **Charged Current (CC) weak inter-action is due to W exchange**



$$\propto \frac{1}{m_W^2 + q^2}$$

- **At low energies: 4 point interaction approximation is sufficient**



$$\propto \frac{1}{m_W^2} \propto \frac{G_F}{\sqrt{2}}$$

- **current current interaction**

$$H_{weak} = G_F \overline{j^{\mu}} j_{\mu} \text{ with } j_{\mu} = \overline{\Psi}\gamma_{\mu}(1-\gamma_5)\Psi$$

combination of vector (V) and axial-vector (A) current

$$V = \overline{\Psi}\gamma_{\mu}\Psi \qquad A = \overline{\Psi}\gamma_{\mu}\gamma_5\Psi$$

Discovered by exhaustive trials with all combinations of S,V,A and T and extensive experimental data

Many distinct states of a Dirac or Majorana ν

Lorentz Transformation

ν^D $\quad \nu_L \quad \bar{\nu}_R \quad \bar{\nu}_L \quad \nu_R$

CPT CPT

Lorentz

ν^M $\quad \nu_L \quad \nu_R$

CPT